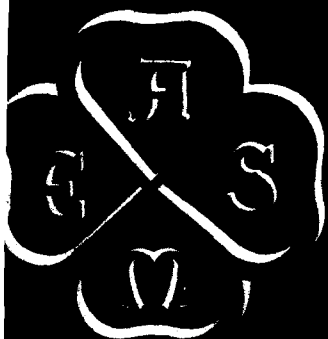


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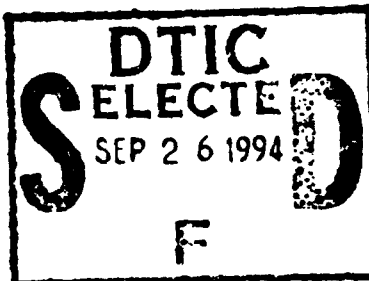
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Evaluation of Unconventional Lubricants at 1200 F in High-Speed-Rolling Contact Bearings

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Several powdered lubricant materials were selected for evaluation in 20-mm-bore-diam angular-contact bearings at 1200 F with an ultimate objective of attaining 10 hr of bearing operation at 50,000 rpm under a combined 50-lb radial load and 50-lb thrust load. To permit operation at these temperatures, bearing materials of titanium-carbide cermet and cobalt-base alloys were chosen and a reliable method of feeding a continuous supply of the powdered lubricant entrained in a gaseous carrier to the bearing was developed.

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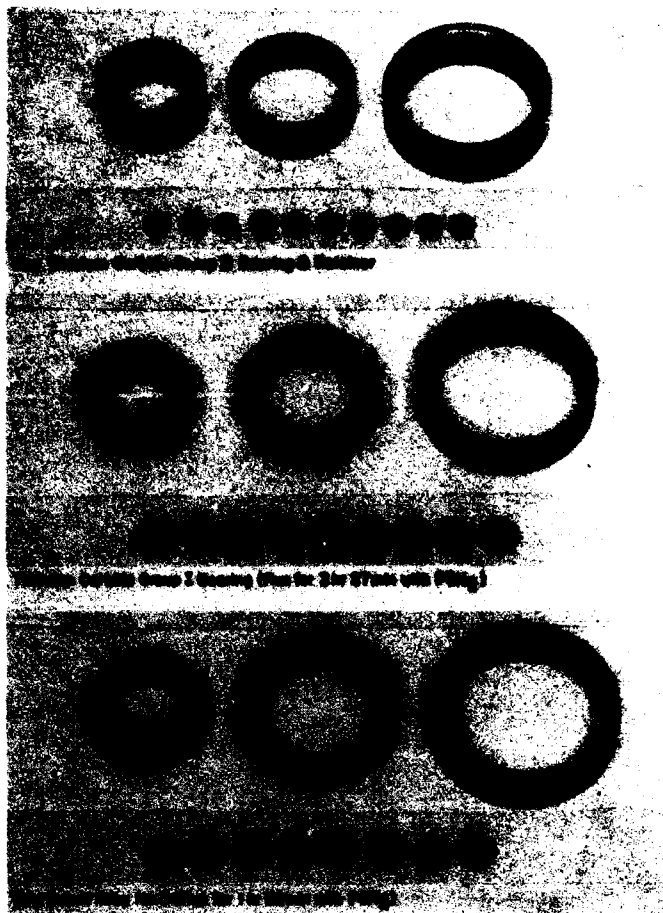


Fig.1 Typical 20-mm bearings

The ever-increasing operating speeds of missiles and aircraft introduce greater demands on equipment within these vehicles due to the associated increase in operating temperature parameters resulting from aerodynamic frictional heating, radiant heat and heat loads generated by additional complex equipment. It is anticipated that future demands will result in operating temperatures beyond the limits of common usage lubricants and bearing materials (1).¹ The purpose of the work presented in this paper was to investigate the use of unconventional types of lubricants in rolling-contact bearings (20 mm bore size) in order to attain bearing operation at 1200 F and speeds to 1×10^6 DN² under combined 50-lb radial and 50-lb thrust loads.

In addition to the limitations encountered with organic fluids as lubricants above 1000 F, consideration also must be given to the limita-

¹ Numbers in parentheses designate References at the end of the paper.

² DN is defined as bearing bore diameter (millimeters) times speed (rpm).

Evaluation of Unconventional Lubricants at 1200 F in High-Speed Rolling Contact Bearings

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tions of the bearing materials at these temperatures. The ability of a lubricant to perform its function under boundary-lubrication conditions may be dependent upon the choice of bearing material to be lubricated. Because of this inter-relationship of bearing material and lubricant, the problem of high-temperature bearing operation was approached as a bearing-lubricant system, subdivided into three general problem areas each dependent upon the other. These are:

- 1 Bearing material and design.
- 2 Lubricant.
- 3 Method of lubricant application.

Investigations by Bowden and Tabor (2) and by Marshall, Peterson and Johnson (3) have indicated the importance of solid surface films between sliding surfaces to reduce wear, friction, and surface damage. From these investigations, it is assumed that the function of a lubricant within a rolling-contact bearing is to form a low shear-strength solid surface film on or between the sliding and rolling contact regions of the bearing to reduce wear and surface damage in these areas. The formation of such a film can be accomplished by either chemical or physical adsorption of the lubricant on the material surface. In either case, the ability of the lubricant to form on the material surface is dependent upon both lubricant and material.

The formation of a film within the contact region of a high-speed, rolling-contact bearing is not always indicative of satisfactory bearing performance. The success of the film is also dependent upon film consistency, hardness, and uniformity as well as the filming or attrition rates of the film. These considerations become more apparent at speeds above 0.4×10^6 DN.

| TABLE 2 COMPOSITION OF BEARING AND RETAINER MATERIAL | | | | | |
|---|--|--|--|---|---|
| Material Identification | | | | | |
| Titanium Carbide Grade K163A1 | Titanium Carbide Grade K162B | Titanium Carbide Grade K175A | Cast Cobalt Alloy | Cast Cobalt Alloy No. 3 | Wrought Cobalt Alloy |
| Manufacturer's Identification | | | | | |
| Kentanium K163A1 | Kentanium K162B | Kentanium K175A | Stellite Star J | Stellite No. 3 | Haynes Alloy No. 25 |
| Composition (Percentage by Weight) | | | | | |
| Ni 33.3 Mo 6.7 TiC 50.0 CbC 10.0 | Ni 25.0 Mo 5.0 TiC 64.0 CbC 6.0 | Ni 40.5 Mo 15.25 Al 4.25 TiC 30.0 CbC 10.0 | Ni 2.5 max Co Bal Cr 32.0 W 17.0 Fe 3.0 max C 2.5 | Ni 3.0 max Co Bal Cr 30.5 W 12.5 Fe 3.0 max C 2.45 | Ni 9.0-11.0 Co Bal Cr 19.0-21.0 W 14.0-16.0 Fe 3.0 max C 0.05-0.15 Si 1.0 max Mn 1.0-2.0 |

| TABLE 1 1200° F BEARING MATERIALS | | | | | | |
|--------------------------------------|-------|------------------------|---------------------------|---------------------------|---------------------------|-----------------------|
| Code No. | Group | Bearing Identification | Inner-Race Material | Outer-Race Material | Ball Material | Internal Bearing Play |
| A | I | Titanium Carbide | Titanium Carbide (K175A) | Titanium Carbide (K163A1) | Titanium Carbide (K163A1) | 0.0010 |
| B | I | Cast Cobalt Alloy | Cast Cobalt Alloy No. 3 | Cast Cobalt Alloy No. 3 | Cast Cobalt Alloy | 0.0028 |
| C | II | Titanium Carbide | Titanium Carbide (K163A1) | Titanium Carbide (K163A1) | Titanium Carbide (K163A1) | 0.0028 |
| D | II | Titanium Carbide | Titanium Carbide (K162B) | Titanium Carbide (K162B) | Titanium Carbide (K162B) | 0.0028 |
| E | II | Wrought Cobalt Alloy | Wrought Cobalt Alloy | Wrought Cobalt Alloy | Cast Cobalt Alloy | 0.0028 |

MATERIALS, APPARATUS AND PROCEDURE

Lubricants

The following three general categories of powdered lubricants were considered for evaluation:

1 Layer-lamellar materials whose structures permit easy slippage of the crystalline structure in one plane (molybdenum disulfide and graphite, for example).

2 Soft solids that tend to bond to surfaces (lead monoxide, for example).

3 Chelating organic solids or thermally stable organic materials that tend to attach them-

selves to metal atoms (metal-free phthalocyanine, for example).

The selection of specific materials from the three general categories was based on thermal stability as well as other known physical and chemical properties. A total of 24 materials was chosen for preliminary stability studies and high-temperature filming experiments. The most promising of these materials was evaluated at 1200 F in a high-temperature rolling-disk machine (as described in reference 4) which was capable of simulating the contact areas in ball bearings. From these preliminary screening appraisals, the following materials were selected to be evaluated in bearings:



Fig. 2 Experimental bearing-retainer configurations

1 Molybdenum disulfide (MoS_2) in a nitrogen environment.

2 Metal-free phthalocyanine in a nitrogen environment.

3 Lead monoxide (PbO) in an air environment.

4 Cadmium oxide (CdO) plus graphite (1:1 mixture by weight) in an air environment.

5 A proprietary organic polymer furnished by Battelle Memorial Institute designated BMI-C. This material was fed to the bearing in a nitrogen-gas environment.

6 Cerium sulfide (Ce_2S_3) in a nitrogen environment.

The atmospheric environment utilized was dictated by the lubricant to be evaluated; that is, nitrogen was used with MoS_2 to prevent lubricant oxidation at temperatures above 800 F, and with metal-free phthalocyanine and BMI-C to improve their ability to form films on the bearing material contact surfaces. Where lubricating ability at 1200 F was not apparently adversely affected, an air environment was utilized.

Bearing Materials

No single material can be considered outstanding for use in the 1200 F range for bearing races, balls, or retainers. Generally speaking, nickel alloys, molybdenum alloys, cobalt alloys, ceramics and cermets are considered to encompass most of the available high-temperature materials. In addition to the primary considerations of fric-

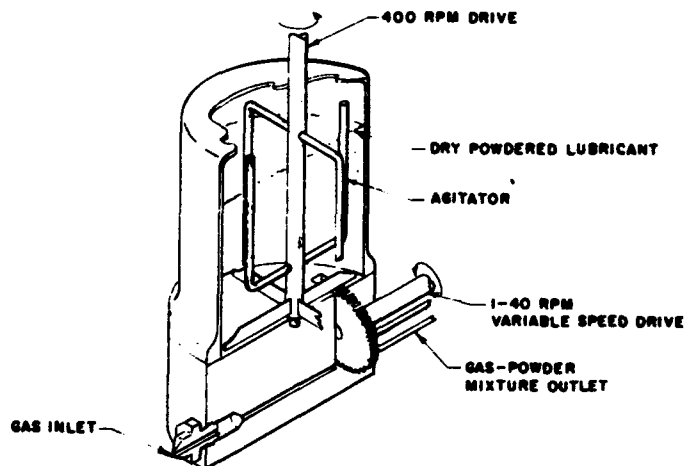
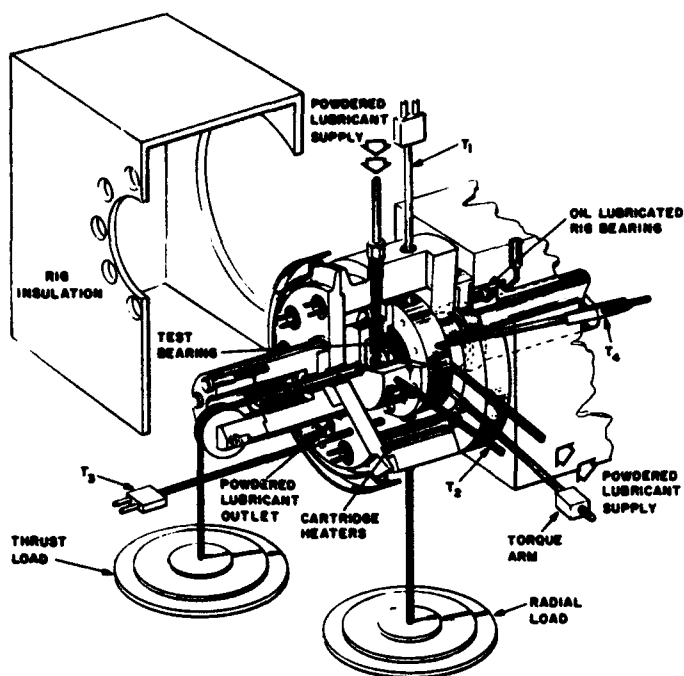


Fig. 3 Variable-speed gear-feed lubricator

tion and wear data, the following factors were also considered for the selection of materials from these groups; strength, hot hardness, thermal stability, and resistance to oxidation at high



NOTE: T₁, T₂, T₃, T₄ ARE THERMOCOUPLE LEADS

Fig. 4 High-temperature combined-load bearing test-rig

temperatures. The final materials chosen for the bearing rolling elements and raceways were selected from the cobalt-alloy family and the titanium-carbide cermets. The specific materials and the actual raceway-ball combinations utilized are presented in Tables 1 and 2.

Several designs of angular-contact 20-mm-bore-size bearings were manufactured for the program. In general, an attempt was made to provide sufficient internal play within the bearing to provide for flow with powdered lubricants and to allow for thermal gradients. Race curvatures were selected to minimize the stress levels within the bearings at maximum speed, load and temperature conditions. At these conditions, the mean compressive Hertz stress on the outer race was calculated to be 150,000 psi for the Group II cobalt-alloy bearings and 215,000 psi for the Group II titanium-carbide bearings (see Table 1). The centrifugal ball load constitutes approximately 30 per cent of the total effective load on the outer race. Counterbored inner-race as well as counterbored outer-race designs were selected for evaluation. Fig. 1 illustrates several bearing configurations.

Retainer materials were selected from the cobalt-alloy family, nickel-alloy family and the titanium-carbide cermets. The grades of material and the retainer designs evaluated are shown in Fig. 2. The grooves in the retainer-guide diameter permit the flow of lubricant through the bearing and allow an exit port for wear debris.

Lubrication Technique

The use of powdered lubricants introduces a flow problem, that is, the assurance that a flow of finely dispersed predetermined quantity of lubricant will be continuously fed to the bearing. A gas is required as a carrier to propel the lubricant particles into the bearing. Several methods were employed to mix the lubricant with the gas. However, control of either the lubricant or the carrier flow rate created a problem.

The final configuration of the lubricant feed apparatus shown in Fig. 3 consists of a gear that picks up lubricant from the upper chamber and carries it between the gear teeth to a point in the housing where the gas carrier blows the powder through the exit line into the bearing. This arrangement permits control of (a) lubricant flow by varying the gear speed and (b) carrier flow by varying the carrier gas pressure. This configuration has proved to be reliable as a supply technique. Such an elaborate device may not be necessary when the lubricant and gas flow rates have been established. Lubricators that have no moving parts have been used successfully for constant flow rates and they would be better suited for applications employing powdered lubricants.

Apparatus

The apparatus used to evaluate lubricant-bearing combinations is shown diagrammatically in Fig. 4. Bearing environmental temperatures to 1500 F are achieved by means of electrical cartridge heaters located in the rig housing surrounding the bearings. Speeds from 5000 to 50,000 rpm are obtained through an air-turbine drive. Radial and thrust loads are applied to the bearing by the use of a dead-weight load system as shown in Fig. 4.

Following is the procedure used to evaluate a lubricant in this combined-load rig:

- 1 Ambient temperature of bearing is raised to 1200 ± 40 deg F as indicated by two thermocouples recording bearing outer-race temperature.

- 2 Thrust and radial loads are applied to bearing; lubrication injection into bearing is started. Lubricant and gas carrier are mixed at room temperature and preheated to approximately 950 F before injection into test bearing.

- 3 After 1 min of lubricant flow, bearing speed is set at 1000 rpm. After 2 min of operation, bearing speed is increased to 25,000 rpm (or other desired operating speed) and a 2-hr run is completed under these conditions. (Bearing torque is checked during speed increase cycle. Lubricant flow is adjusted to maintain minimum torque level.)

- 4 Reverse procedure is followed to shut down apparatus at completion of bearing run or when it

is necessary to stop run prematurely due to rough operation or bearing failure.

5 Lubricant effectiveness is determined from bearing microscopic and macroscopic inspections and from bearing dimensional and weight changes.

RESULTS AND DISCUSSION

Bearing-Lubricant Evaluation

Research concerning lubricating qualities has been conducted during recent years on such materials as molybdenum disulfide and lead monoxide. However, information about their ability to function in rolling-contact bearings at high speeds and temperatures of 1200 F (6) was limited. The primary consideration in using these materials, therefore, was to determine their effect in high-speed bearings, operated at temperatures of 1200 F.

The known oxidation characteristics of molybdenum disulfide dictated the use of a nitrogen carrier. Nitrogen was not needed for lead monoxide at the 1200 F condition. The other materials selected for lubricants in bearing experiments (metal-free phthalocyanine, cerium sulfide, BMI-C and the graphite plus cadmium-oxide mixture) were evaluated previously in the laboratory to determine their ability to form a film on the bearing material. Except for the graphite-cadmium oxide mixture, nitrogen was used as the gas carrier to limit the effect of oxidation. The results of these evaluations are listed in Table 3. Following is a discussion of each lubricant.

Molybdenum Disulfide

The most successful bearing operation at 1200 F in terms of bearing wear and smoothness of operation was conducted with molybdenum disulfide. Wrought cobalt-alloy bearings have been run for periods to 11½ hr at speeds of 25,000 to 30,000 rpm under 50-lb thrust load; they have also been run for periods to 6 hr under the same conditions with combined radial and thrust loads of 50 lb each being applied. This lubricant was run in both cast cobalt-alloy and titanium-carbide bearings for periods of 3 hr with equal success. Bearing torque characteristics at 1200 F using molybdenum disulfide are shown in Fig.5.

Light pitting beneath the lubricant film in the bearing contact regions was evident in both materials. Table 2 lists the findings concerning two bearings lubricated with MoS₂ and run at 1200 F. Operation at speeds in excess of 30,000 rpm resulted in vibrations in the bearing due to the relatively rough film of lubricant in the running tracks of the raceways. (The consistency of this film is dependent upon lubricant flow

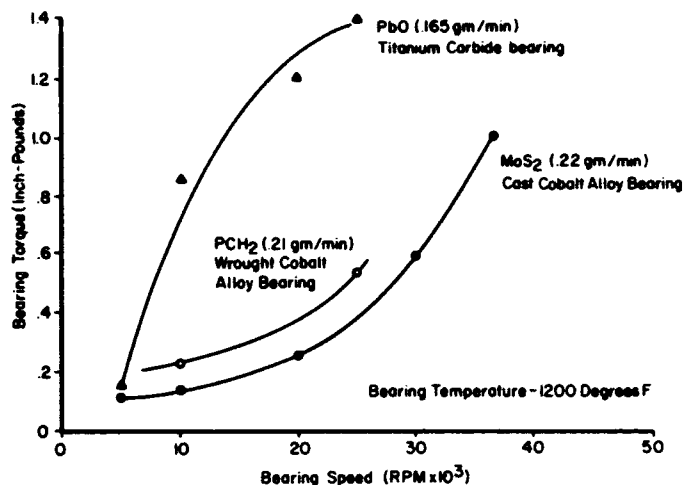


Fig.5 Bearing-lubricant torque characteristics

rates and lubricant particle size.) Lubricant flows above 0.48 gram per min resulted in a substantial (0.0003 in.) film buildup during 3-hr periods of operation at speeds of 25,000 rpm. At reduced flow rates below 0.20 gram per min, wear was encountered. Recent investigations using MoS₂ indicate that smooth operation to speeds of 35,000 rpm is possible using submicron-size (below 0.00008 in.) particles at a flow rate of 0.20 to 0.25 gram per min in contrast to the rough operation encountered with the relatively coarse (0.0008-0.0010 in.) lubricant used during the earlier runs.

Metal-Free Phthalocyanine

Laboratory evaluations with metal-free phthalocyanine (6) indicate that decomposition of the lubricant commences above 900 F. The rate is sufficiently low to permit the lubricant to perform its functions and to be replenished before complete decomposition occurs. This characteristic results in very clean operation of the bearing and rig with a negligible quantity of decomposed particles present after the completion of a run. The ability of the phthalocyanine to form a film on the bearing surfaces has been attributed in part (6) to its chelating properties; that is, the ability to attach itself firmly to most metal atoms. The rate at which filming occurs on the cobalt-alloy and titanium-carbide bearings at 1200 F, however, has not proved rapid enough to prevent bearing wear. An average internal wear rate (which represents the combination of eight contact surfaces) is approximately 0.001 in. per hr in both cobalt-base alloy and titanium-carbide material bearings. Bearing operation is generally smooth with a minimum of vibration. Slight difference was evident in performance between the cobalt-base alloy and titanium-carbide bearings

TABLE 3

SUMMARY OF EVALUATIONS OF POWDERED LUBRICANTS USED IN 20 MM ANGULAR CONTACT BEARINGS (1)

O P E R A T I N G C O N D I T I O N S

R E S U L T S

--- BEARING WEAR ---

| Run No. | Bearing Code (2) | Lubricant (3) | Lubricant Flow Rate (gm per min) | Carrier Gas (lit per min) | Average Outer-Race Temperature (degrees F) | Bearing Speed (rpm) | Operating Time at Speed (hr:min) | Reason for Termination of Test | Change in Internal Clearance (4) (inch) | | | | Weight Loss Percentage (5) | | REMARKS |
|---------|------------------|----------------------|----------------------------------|---------------------------|--|---------------------|----------------------------------|--------------------------------|---|------------|--------|----------|----------------------------|------------|---|
| | | | | | | | | | Inner Race | Outer Race | Balls | Retainer | Inner Race | Outer Race | |
| 23 | E-48 | MoS ₂ | 1.5352 | Nitrogen 0.77 | 1235 | 25,000 to 27,000 | 11:33 | Bearing Inspection | +0.0005 | -0.846 | -0.077 | -0.573 | -2.237 | | Bearing remained operable; heavy rough film in raceway. |
| 100 | C-28 | MoS ₂ | 0.663 | Nitrogen 0.70 | 1235 | 29,000 | 2:10 | Bearing Inspection | +0.0003 | -0.0019 | +0.012 | -0.0094 | +0.014 | | Run started at 800 degrees F. All contact surfaces dark polished. Inner race pitted. |
| 13 | A-1G | PCB ₂ (6) | 0.538 | Nitrogen 0.40 | 1230 | 21,000 | 3:27 | Lubricator Failure | -0.0043 | -0.008 | -0.223 | -0.885 | -3.930 | | All surfaces dark polished. Fine pitting and wear on contact surfaces. Soft scale on fringes of tracks. |
| 26 | E-48 | PCB ₂ (6) | 0.433 Average | Nitrogen 0.67 | 1260 | 25,000 to 30,000 | 3:06 | Erratic Operation | -0.0035 | -0.122 | -0.078 | -2.366 | -1.534 | | Surfaces polished with spotty bluish areas. Inner race worn unevenly. |
| 7 | B-1R | POO | 0.0367 | Air 1.34 | 1250 | 23,800 | 1:03 | Bearing Inspection | -0.0086 | -0.412 | -0.108 | -1.624 | +0.250 | | Contact surfaces had smooth dark polish with thin pitted dark film evident. |
| 14 | E-1G | Graphite + CoO | 0.0331 | Air 0.84 | 1200 | 20,000 | 0:06 | Erratic Operation | -0.0009 | +0.013 | -0.028 | +0.178 | -0.206 | | Contact surfaces had silver appearance. Spotty adherent bluish buildup evident on all surfaces. |
| 25 | E-1G | CoS ₂ | 0.4484 | Nitrogen 0.67 | 1262 | 25,000 | 0:22 | Erratic Operation | -0.0070 | -0.235 | -0.196 | -3.733 | -0.882 | | Heavy wear with pitted rough surfaces. |
| 24 | E-1G | BMI-C | 0.2835 | Nitrogen 0.67 | 1270 | 100 to 20,000 | 0:17 | Erratic Operation | +0.0011 | +0.006 | -0.002 | -0.046 | -0.111 | | Hard crusty film buildup; rough surfaces. |

Notes:

- (1) Thrust load of 52 lb. applied to bearing during all runs except last 3 hours and 52 minutes of run 23, which was conducted with 53 lb radial and 52 lb thrust loads.
- (2) Bearing code identification is defined in Table 1 and Figure 2 as follows:
For E-48: E is defined in Table 1 as a Group II wrought cobalt alloy bearing;
48 is defined in Figure 2 as a cast cobalt alloy No. 3 retainer.
- (3) Lubricant particle average-size range: 10 to 25 microns.
- (4) Plus (+) sign indicates loss in internal play, or buildup of lubricant.
- (5) Plus (+) sign indicates weight gain.
- (6) Phthalocyanine radical is expressed as PC in this report; thus metal-free phthalocyanine is expressed as PCB₂, and metal phthalocyanine is expressed as PCM.

although operation was considered slightly smoother with titanium-carbide bearings. In both bearings, insufficient lubricant was indicated by highly polished contact surfaces and fine pitting. At increased flow rates, the bearing contact surfaces had a dark polish and myriads of minute pits.

Lead-Monoxide, Graphite Plus Cadmium-Oxide Mixture, BMI-C and Cerium Sulfide

Only initial lubricant screening runs instead of endurance evaluations were conducted with these lubricants. These evaluations consisted of only one or two short bearing runs. The initial investigations, however, provide a good indication of the effectiveness of the lubricant in an actual bearing and the merits of further evaluating the lubricants for high-speed bearing applications.

Lead monoxide was characterized by smooth operation in a cobalt-base alloy bearing. At the lowest flow rate attempted, 0.036 gram per min, internal wear on the rolling-contact surfaces was high although the wear on the retainer sliding surfaces was negligible. At an increased flow rate of 2.13 grams per min, the lubricant tended to clog the bearing inducing high bearing torques as shown in Fig.5 finally resulting in a sudden speed decrease after 25 min of operation. A film formed on all contact surfaces with no detectable wear being evident. Additional evaluations were not conducted with this lubricant at intermediate flow rates and, therefore, an optimum flow was not established.

The use of the graphite plus cadmium-oxide mixture indicated very rapid buildup on the contact surfaces of a cobalt-base alloy bearing during a period of only 6 min at a flow rate of 0.033 gram per min. It is believed that this material offers considerable merit as a lubricant at properly adjusted flow rates. More recent evaluations indicate that this lubricant will function well at bearing speeds of 30,000 rpm over the temperature range from 100 to 1200 F for periods to 10 hr in an air environment. In contrast, the cerium sulfide appeared to offer no protection to the bearing surfaces.

The organic polymer (BMI-C) appeared to have filmed readily on both cobalt-base alloy and titanium-carbide bearings. The film formed, however, was hard and crusty causing rough operation that required the termination of testing.

In addition to the results obtained with various lubricants, several other factors are worth noting:

1 Oil run-in prior to operation using powdered lubricants appeared to offer no improvement in bearing performance.

2 The axial grooving of the retainer-guide diameter to provide adequate lubricant flow passage consistently resulted in guide-diameter wear. The wear with this configuration, it was believed, was due in part to the scraping action of the grooves which tended to remove the lubricant-film buildup from the race-locating diameter. Unsuccessful attempts were made to eliminate this condition by removing sharp edges. Similar wear was encountered with both inner and outer-race riding grooved retainers. An uninterrupted guide diameter appeared to offer an improvement over this design.

3 Inner-race wear was generally greater for outer-race riding retainer bearings and the outer-race wear was generally greater for inner-race riding retainer bearings when lubricant flow rates were marginal. This indicates that the retainer may trap more lubricant in the raceway of the race on which it guides, thus furnishing better lubrication in that region.

4 It was determined during operation that the wrought cobalt-alloy material was not dimensionally stable for long periods of time at 1200 F after being cold-reduced 40 per cent and aged 4 hr at 1140 F. A uniform size reduction was noted in the range of 0.00027 in. per in. of diameter in 13 hr at 1200 F and a further reduction of 0.00024 in. per in. of diameter after an additional 14 hr at 1200 F. This problem of dimensional instability was not encountered in the cast cobalt or titanium-carbide materials during periods to 10 hr at 1200 F.

In addition to the problems associated with a high-temperature bearing lubrication system, consideration must also be given to thermal gradients and differential expansions encountered in both rig and bearing components. However, with an understanding of the problems common to high-temperature applications, it is believed that a reliable high-speed (25,000 rpm) rotating device could be developed. The results of the work now completed indicate the feasibility of operating rolling-contact bearings in such a device at temperatures of 1200 F for periods of at least 10 hr. Work is presently continuing to investigate the room-temperature to 1200-F range of powdered lubricants. In a practical application, lubricant supply rates for two support bearings would be in the order of 1 lb of lubricant for 10 hr of operation, assuming the use of a noncirculating system. As investigations continue, optimum flow rates are being more closely pinpointed and may result in a reduction in this total flow requirement. Carrier gas for such a system might be compressed gas for molybdenum disulfide or ram air and engine exhaust gas could be considered as other lubricants such

as a graphite plus cadmium-oxide mixture are more fully explored.

CONCLUSIONS

The work conducted during this program has indicated the feasibility of utilizing solid lubricants in a continual injection-type system for lubricating rolling-contact bearings at temperatures of 1200 F for periods of at least 10 hr. The maximum bearing capabilities have not been explored fully but operation at 25,000 to 30,000 rpm (0.5×10^6 DN) under combined radial and thrust loads of 50 lb is possible. These results have been obtained in wrought cobalt-alloy bearings with molybdenum disulfide although powders such as metal-free phthalocyanine and lead monoxide have shown some promise at these temperatures. The degree of bearing wear and smoothness of operation are dependent upon the type and characteristics of the lubricant film formed on the bearing-contact surfaces. The formation of such a film is a function of both the lubricant and the bearing material, the degree of filming being dependent upon the affinity of the former for the latter. Investigations are continuing to extend the operational range of solid lubricants from 70 to 1200 F in actual bearing evaluations. Additional solid lubricants are also being screened and it appears that combinations and mixtures of solid lubricants, when effectively applied, will permit operation of rolling-contact bearings over a temperature range of 70 to 1200 F at speeds to 30,000 rpm for periods of at least 10 hr.

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